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Early Cretaceous foreland sedimentation of the lower clastic unit Kootenai Formation southern Gallatin County Montana

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EARLY CRETACEOUS FORELAND SEDIMENTATION OF THE LOWER CLASTIC UNIT, KOOTENAI FORMATION, SOUTHERN GALLATIN COUNTY, MONTANA

by

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ABSTRACT

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Early Cretaceous Foreland Sedimentation of the Lower Clastic Unit, Kootenai Formation, Southern Gallatin County, Montana (57 pp.)

Director: Dr. Johnnie N. Moore

Cobble to pebble conglomerate and sandstone comprising the Early Cretaceous basal Kootenai Formation in southwestern Montana record the initial erosion of western Cordilleran highlands. Transport of coarse debris is recorded in this widespread but thin basal deposit. Deposition was predominantly by braided channels although evidence for minor deposition by debris flows does exist. Remnant longitudinal and transverse bars and channel fill sequences reflect a system of braided channels which distributed and reworked coarse material over a moderate relief topography, possibly an alluvial plain environment near the foreland basin's western margin. Overlying this initial deposit are fining up sandstone and mudstone sequences. Minor calcareous mudstones represent areas of ponded drainage where ephemeral lakes developed. Finer-grained sandstone, siltstone, mudstone and calcareous mudstone lithologies predominate in the upper part of the "lower clastic unit". This entire sequence records a change in environment from one of transport by braided channels to one of deposition by higher sinuosity channels. Aggradation within the basin coupled with erosion of the highlands to the west resulted in this overall fining-upward sequence.

ACKNOWLEDGMENTS

I wish to thank Drs. Johnnie Moore, Howard Reinhardt and Don Winston for the help they gave me and for the time they spent reading the manuscript. Their suggestions and encouragement are appreciated. I would also like to thank Dr. James Peterson for the many discussions concerning carbonate petrology, and Dr. Lee Suttner for the discussions we had concerning the Kootenai Formation. Mark Stearns is also thanked for considerable help in the field.

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INTRODUCTION

The Kootenai Formation and correlative strata comprise a part of the Early Cretaceous foreland basin sequence which records the effects of initial foreland folding and thrusting. The "lower clastic unit" of the Kootenai Formation of Neocomian (?) to Aptian age (Moberly, 1960 and Suttner, 1969) records the earliest of this tectonically-controlled sedimentation in southwestern Montana (Fig. 1). General depositional environments of the entire Kootenai Formation in parts of Montana were studied by Suttner (1969), Walker (1974), and Roberts (1972). Early studies by Cobban (1955), Kauffman (1963), McQuire (1957), Gwinn (1965) and Peck (1957) were mainly stratigraphic. Detailed environmental studies exist only for the upper Kootenai, Gastropod limestone (James, 1977). Environmental interpretation for the "lower clastic unit" of the Kootenai Formation has ranged from desert pavement pediment veneer (Peterson, 1966 and Stokes, 1944), to some type of fluvial deposit of an alluvial plain or distal alluvial fan (Suttner, et al., 1981 and Roberts, 1972).

I propose that the "lower clastic unit" was deposited by two different fluvial systems. The basal "lower clastic unit" was deposited by a braided fluvial system which was replaced through time by a higher sinuosity fluvial system. These fluvial systems deposited sediment on an alluvial plain of the Cordilleran foreland basin. Clastic detritus within the "lower clastic unit" is similar to other Earliest Cretaceous deposits in the foreland basin. These deposits

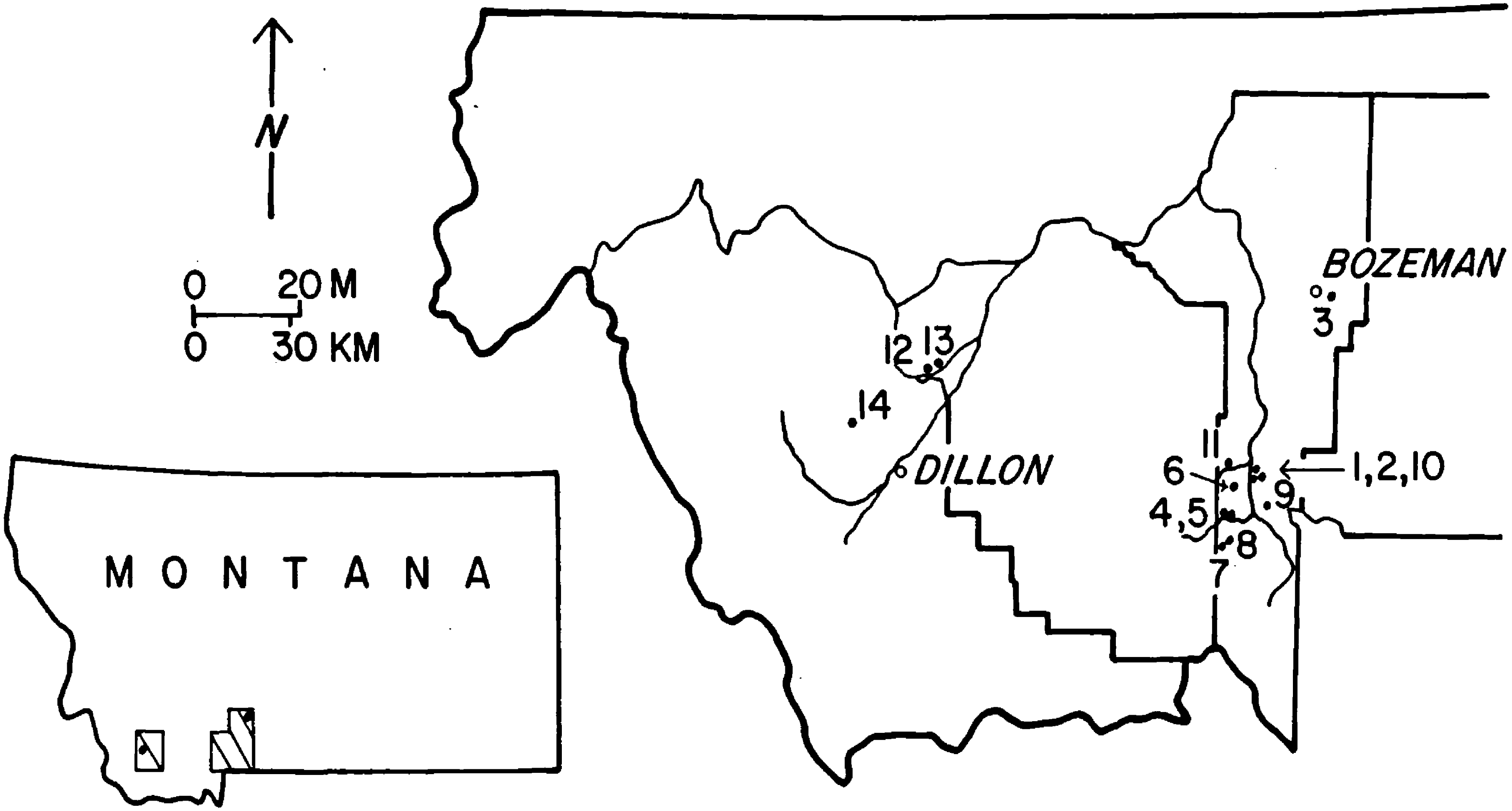


Figure 1. Location of measured sections, "lower clastic unit", Kootenai Formation in the Bozeman and Dillon areas of southwestern Montana.

reflect a provenance of sedimentary rocks such as the miogeoclinal Paleozoic and Early Mesozoic sediments derived from areas west of Montana.

TECTONIC SETTING

By Late Jurassic time, an Andean-type margin and associated batholithic emplacement were established along the length of western North America (Davis, et al., 1978). At this same time, in the eastern Cordillera, the intracratonic Sundance Sea regressed to the north exposing a broad marine shelf and plain on which initial foreland basin sediments accumulated (Peterson, 1966). Continental, foreland basin deposits, derived from thrusted Paleozoic and Early Mesozoic miogeoclinal sediments to the west and southwest covered this previous marine plain until Mid-Cretaceous time, when marine conditions once again transgressed the mid-continent (Roberts, 1972 and McGookey, 1972). Correlation between continental clastic deposits for the Early Cretaceous exists from north-central British Columbia, south of the Peace River Arch, through Montana and the Colorado Plateau (Peterson, 1966; Armstrong and Oriel, 1965; Stelck, 1975; McMannis, 1965; Christopher, 1975; Roberts, 1972 and MacKenzie and Ryan, 1962). These Earliest Cretaceous deposits are composed of conglomerates and conglomeratic sandstones with consistent lithologies of quartzite and chert pebbles, resembling Paleozoic sediments (Eisbacher, et al., 1974; Suttner, 1969; Eyer, 1969; Moberly, 1960 and Furer, 1970) (Table 1).

In southwestern Montana, no major source for the Early Cretaceous conglomeratic sequence has been established. However in southeastern Idaho, depositional constraints on the movement of the Paris

Table I. Kootenai Formation and Correlative Strata (taken from: Stott, 1975; Christopher, 1975; Moberly, 1960 and Roberts, 1972)

m.y.B.P.	FOOTHILLS PEACE RIVER B.C.	SOUTHERN ALBERTA FOOTHILLS	NORTH CENTRAL MONTANA	SOUTHWEST MONTANA (this paper)	BIG HORN BASIN WYOMING	IDAHO-WYOMING BORDER	COLORADO PLATEAU
ALBIAN	FT.ST. JOHN GROUP	BEAVER MINES FM	FALL RIVER		SYKES MTN FM		"DAKOTA" FM
124 (?)			FUSON SH			SMOOT FM	
				UPPER CALCAREOUS UNIT	HIMES MB	DRANEY LS	
LOWER CRETACEOUS	BULLHEAD GROUP	BLAIRMORE GROUP	KOOTENAI FORMATION	KOOTENAI FORMATION	CLOVERLY FORMATION	GANNETT GROUP	
APTIAN			3 RD Cat CREEK SS	UPPER CLASTIC UNIT		BECHLER FM	BURRO CANYON FM
						PETERSON LS	
				LOWER CALCAREOUS UNIT	LITTLE SHEEP MDST. MB		
	GETHING FM	GLADSTONE FM					
			LAKOTA SS	LOWER CLASTIC UNIT	PRYOR CONGL.		BUCKHORN CONGL.
129 NEOCOMIAN						EPHRAIM CONGL	
PORTLANDIAN			MORRISON FM	MORRISON FM	MORRISON FM		MORRISON FM

thrust suggest emplacement from Late Jurassic to Early Cretaceous time (Jordan, 1981; Armstrong and Oriel, 1965 and Royse, et al., 1975). This uplift resulted in deposition of the Ephraim Conglomerate, the upper part being lithologically and biostratigraphically correlative to the "lower clastic unit" (Peterson, 1966 and Eyer, 1969). Armstrong and Oriel (1965) suggested that a north-south trending trough adjacent to the thrusted highlands received clastics eroded from this early phase of thrusting. To the north, in southern Alberta, the Lower Blairmore Group contains conglomerates with similar clasts of chert and quartzite and is lithologically equivalent to the basal Kootenai Formation. Both the Upper Ephraim Conglomerate of the Gannett Group and the Lower Blairmore Group are thicker and coarser than the "lower clastic unit" of the Kootenai Formation in Montana.

It appears that early pulses of foreland folding and thrusting may have created a source terrane for the "lower clastic unit". Jordan (1981) showed that the mechanism of crustal subsidence due to stacking of thrust sheets adequately accounts for Early Cretaceous foreland basin sedimentation. Suttner and others (1981) suggested that isostatic uplifts associated with the early emplacement of the Idaho Batholith to the west are the source for the "lower clastic unit". This possibility as well as the thrust plate possibility as source terranes for the "lower clastic unit" are consistent with the regional tectonic schemes for this time. Support for the thrust plate source terrane is found in the southern equivalents of the Kootenai Formation where the deposition of thick conglomeratic sequences has been attributed to early foreland thrusting (Armstrong and Oriel, 1965 and Royse, et al., 1975).

STRATIGRAPHY AND SEDIMENTATION

Kauffman (1963), informally recognized four units of the Kootenai Formation in northwestern Montana. These are the lower clastic, lower calcareous, upper clastic and upper calcareous units. This terminology can be extended to outcrops in southwestern Montana. The "lower clastic unit" crops out in southwestern Montana as a resistant conglomerate and sandstone ledge overlain by a slope forming sequence of siltstones and shales in the Bozeman (eastern) area and as repetitious, tabular sandstones encased in maroon siltstones and shales in the Dillon (western) area. The "lower clastic unit" unconformably overlies the Jurassic Morrison Formation. The gradational contact between the "lower clastic unit" and the overlying "lower calcareous unit" occurs above a distinct, muddy sandstone to calcareous sandy mudstone which is present in eastern area exposures. When this is not present, the boundary between the two is placed where sand-sized clastic material is no longer the dominant lithology or at the first limestone bed. I delineated lithofacies within this sequence on the basis of composition, size and shape of the depositional units and their relation to surrounding lithologies. I designated lithofacies following that of Miall (1978) (Table II). Miall's lithofacies designations are descriptive, being based on lithology of braided river deposits. Since the designations are descriptive, I am expanding the usage to include those deposits interpreted here as high sinuosity river deposits. Interpretation

Table II

(Taken from Miall, 1978)

Lithofacies classification of Miall (1978)

Lithofacies Code	Lithofacies	Interpretation
Gm	massive or crudely bedded gravel	longitudinal bars, lag deposits, sieve deposits
Gms	massive, matrix supported gravel	debris flow deposits
St	sand, medium to very coarse, may be pebbly	dunes (lower flow regime)
Sp	sand, medium to very coarse, may be pebbly	Linguoid, transverse bars, sand waves (lower flow regime)
Sh	sand, very fine to very coarse, may be pebbly	planar bed flow (upper and lower flow regime)
Sr	sand, very fine to coarse	ripples (lower flow regime)
She, Spe	sand	aeolian deposits (analogous to Sh,Sp)
Fm	mud, silt	overbank or drap deposits
P	carbonate	soil

Lithofacies classification modified from Miall (1978) This study

Lithofacies Code	Lithofacies	Interpretation
Gm_1	massive or crudely bedded gravel	longitudinal bar, lag deposits
Gm_2	stratified sand and gravel, may be graded	channel fill
Gms	massive, unsorted, matrix supported gravel	debris flow deposits
St	sandstone medium to coarse	dunes (lower flow regime)
Sp	sandstone fine to coarse	transverse bars, sandwaves (lower flow regime)
Sh	sandstone fine to medium size-graded	planar bed flow (lower flow regime)
Sr	sandstone fine to medium	ripples
Sre	sandstone very fine to fine	aeolian ripples
Fm	mud, silt	overbank deposits
P	calcareous mud	vadose zone early cement ephemeral lake deposits

of lithofacies occurring in this study agree with interpretations provided by Miall (1978), however frequency of occurrence of individual lithofacies differs from those in braided systems.

Conglomeratic Lithofacies Gm and Gms

Description

The dominant lithologies of the basal "lower clastic unit" are cobble to pebble conglomerate, conglomeratic sandstone and granule to fine-grained sandstone. These lithologies comprise three lithofacies: 1) massive, grain-supported conglomerate, Gm_1; 2) interbedded to graded conglomerate and sandstone, Gm_2, and 3) unsorted, matrix-supported conglomerate, Gms. Deposits of these lithofacies occur as lenses which range from small pods 0.5 feet (0.1 m) thick and 2.0 feet (0.6 m) wide to lenses 4.5 feet (1.4 m) thick that are traceable across the outcrop for at least 300 feet (91. m). Contacts between lenses are most commonly sharp and scoured.

The massive, grain-supported conglomerate lithofacies (Gm_1), is well exposed in the Dillon or western areas. Here the conglomerate consists of moderately to poorly sorted small boulders, cobbles and pebbles in an 11.0 foot (3.3 m) thick bed containing crude horizontal stratification. Graded bedding and cross-stratification are not present. The overall outcrop shape is tabular. Pebble imbrication on bedding surfaces were observed at one locality (section 12). To the east, in the Bozeman area, the massive, grain-supported conglomerate lithofacies (Gm_1), consists of massive to crude horizontally stratified conglomerate with imbricated pebbles. The coarsest material consists of small cobbles. The lithofacies is moderately to poorly sorted and occurs in variably sized, lens-shaped deposits. The massive, grain-supported conglomerate lithofacies (Gm_1) is interlenses with the interbedded to graded conglomerate and sandstone lithofacies (Gm_2) in the Bozeman area. This lithofacies (Gm_2) is the most commonly observed lithofacies in the basal "lower clastic unit". Textures in the Gm_2 lithofacies range from massive to horizontally bedded and some grade from pebble conglomerate to granule and medium-grained sandstone (Fig. 2); larger clasts within the conglomerate show a preferred orientation. Deposits of this lithofacies vary in size from small pods of conglomerate surrounded by coarse-grained sandstone to lenses of interbedded conglomerate and sandstone 1.0 to 4.5 feet (0.3 to 1.4 m) thick and 7 to approximately 300 feet (2.1 to approximately 91. m) wide. Thin sandstone stringers within conglomerate and reverse grading are present locally. Lenses of these two lithofacies (Gm_1 and Gm_2) overlap and truncate each other laterally and vertically giving rise to scoured and sharp contacts.

The third lithofacies has a texture which may be described in outcrop as "poured-in-looking". This massive, unsorted, matrix-supported, pebble conglomerate (Gms), has sharp basal contacts which do not scour underlying lithologies and upper contacts which grade into pebbly sandstone or ripple-laminated sandstones (Fig. 3). Little mud or silt matrix is present. Thicknesses range from 1.5 to 4.5 feet (0.5 to 1.4 m). Lateral extent was not determined due to poor exposure.

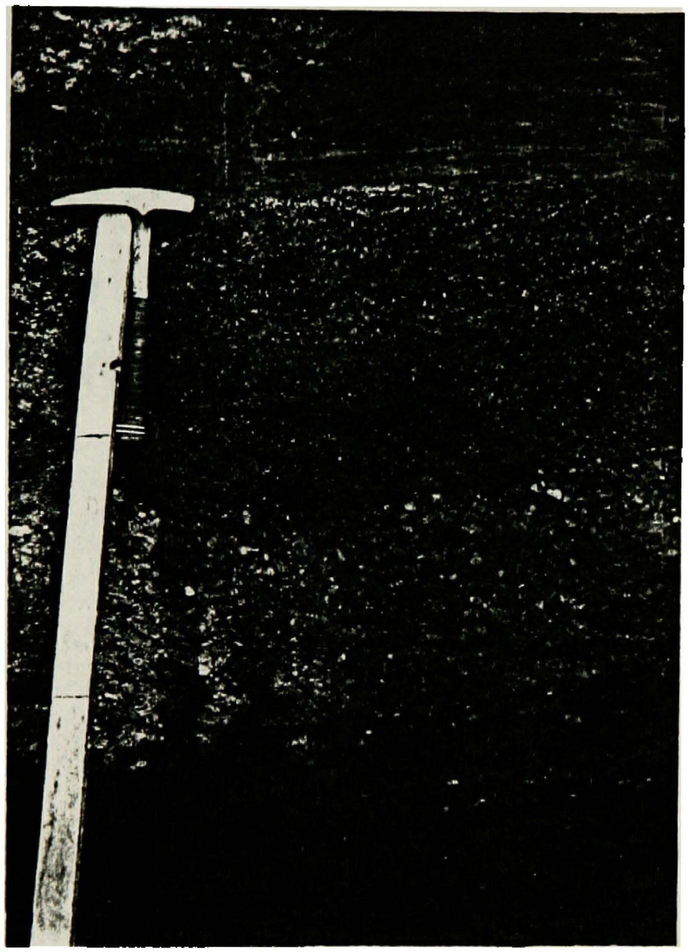
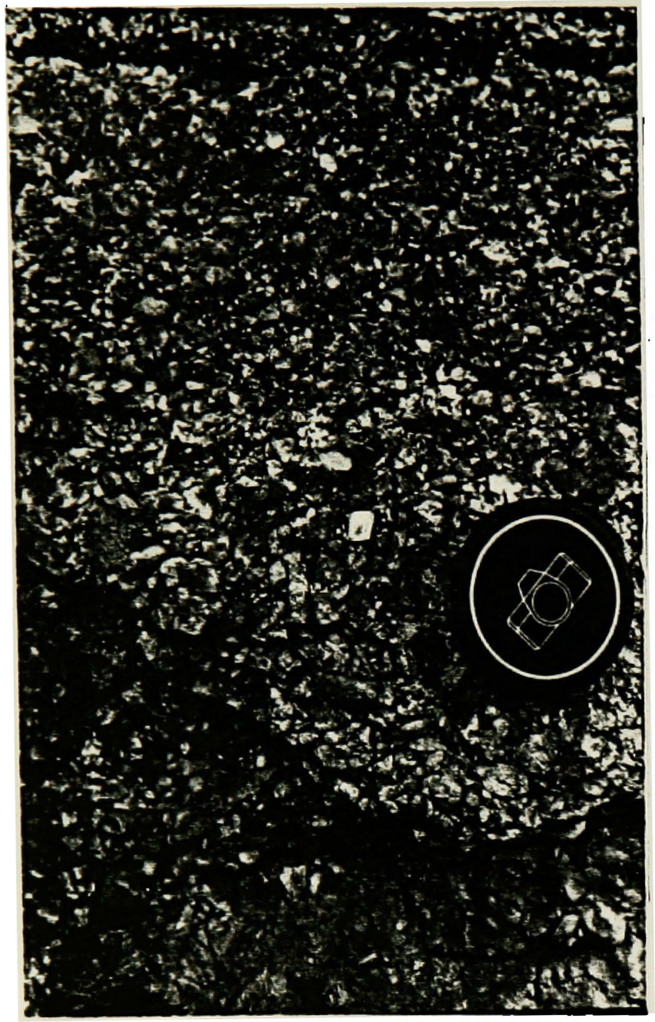
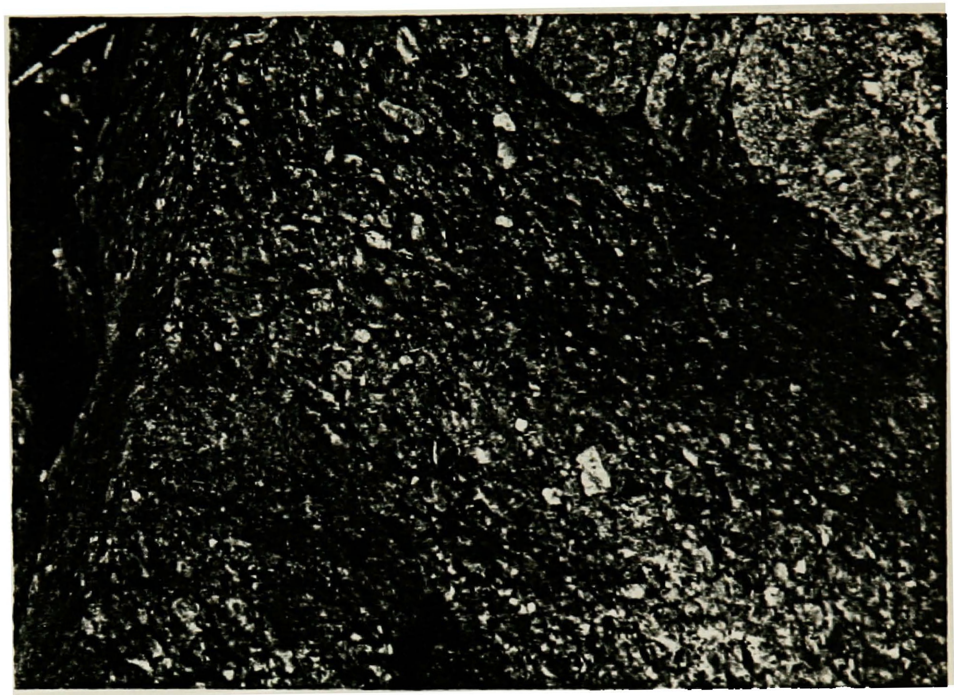


Figure 2. The Gm_2 lithofacies at section 5. A graded sequence of large pebble conglomerate to granules is overlain by ripple cross-laminations (lithofacies Sr) and low angle megaripples. The Gm_2 lithofacies overlies pebbly trough cross-bedded sandstone (lithofacies St). Jacobs staff in feet.



3a



3b

Figure 3. Comparison of grain supported framework in fluvially deposited conglomeratic lithofacies (Gm_1 and Gm_2) (3a), with matrix-supported conglomerate of probably debris flow origin (lithofacies Gms)(3b). Scale 8" left to right in 3b.

Interpretation

Incomplete longitudinal bar and channel fill sequences are recorded in the massive, grain-supported (Gm_1) and interbedded to graded conglomerate and sandstone (Gm_2) lithofacies. Stratification within longitudinal bar and channel fill sequences have been described from glacial outwash streams by Smith (1974), Eynon and Walker (1974), Boothroyd and Ashley (1975), Gustavson (1974), Rust (1972), and Hein and Walker (1977). Horizontal bedding represents transport of gravel in sheets and imbrication represents clasts which were free to roll and respond to currents present during and after deposition (Walker, 1975 and Smith, 1970). High energy, competent streams are necessary to transport coarse bedload in sheets (Allen, 1977). In both recent and ancient braided stream deposits, coarse-grained material with massive to crude horizontal stratification and common clast orientation have been interpreted as deposits of longitudinal bars (Boothroyd and Ashley, 1975; Gustavson, 1974; Hein and Walker, 1977; Rust, 1978 and Miall, 1977). On the South Platte River, Smith (1970) found that longitudinal bars formed mainly in coarse-grained material. In the Precambrian Van Horn Sandstone of West Texas, McGowen and Groat (1971) interpreted parallel bedded, lens-shaped, convex upper surface, gravel deposits as longitudinal bars.

The massive conglomerate lithofacies (Gm_1) exhibits characteristics described from deposits of longitudinal bars. Transport of bedload in sheets under high stream power conditions resulted in deposition of this lithology. The presence of crude horizontal stratification and pebble imbrication and a spatial relationship with the interbedded to graded conglomerate and sandstone lithofacies (Gm_2) suggest a longitudinal bar origin for the massive conglomerate lithofacies. Eynon and Walker (1974) in studying a large Pleistocene bar, interpreted thin sand layers within crudely stratified, imbricate gravels as braided channel fills. They interpreted the sands as deposited from a waning current over a gravel lag. Gustavson (1974) found that deposition in channels of a braided outwash fan in Alaska consisted of gravel laid down during upper flow regime conditions followed by late stage thin patches of horizontally stratified sand. McGowen and Groat (1971) interpret alternating sand and gravel beds which flank horizontally stratified gravels as channel fill flanking longitudinal bars. Steel (1974) records a similar association in his study of the New Red Sandstone.

The interbedded conglomerate and sandstone lithofacies (Gm_2) is interpreted as channel fill deposits for the following reasons: a spatial association with massive conglomerate which represents deposits of longitudinal bars, and a texture and stratification indicative of changing flow. Graded conglomerate and variously sized lenses and pods of conglomerate in sharp to eroded contact with cross-stratified sandstones reflect waning and varying flow strengths. Deposits reflecting variable flow conditions are characteristic of braided channel deposits (Allen, 1977).

Matrix-supported clasts and non-erosive basal contacts indicative of viscous flow occur in the unsorted, matrix-supported conglomerate lithofacies (Gms). Deposits from highly concentrated fluids flow in a laminar fashion as opposed to turbulent flow exhibited by less concentrated fluids (Fisher, 1971). Concentrations in a fluid vary from water laid debris floods to highly viscous debris flows. Although debris flows are generally described as rich in silt and clay material, some have been documented with little clay matrix (Fisher, 1971). Debris flows containing a small portion of silt and clay will exhibit properties similar to those of debris flows rich in silt and clay (Miall, 1970, and Fisher, 1971). Debris flows have been described as massive, lacking internal stratification, poorly sorted and thick, with slight to non-erosive basal contacts. In some cases, they contain reverse grading and clast orientation parallel to flow (Miall, 1970; Sharp and Nobles, 1953; Steel, 1974; Hooke, 1967 and Fisher, 1971). Steel (1974) interpreted conglomerates in the New Red Sandstone (with massive texture, poor sorting and little erosion at the base, overlain by a bed of sandstone) as mudflow deposits. Hooke (1967) likewise described similar characteristics for debris flows on alluvial fans in California. Miall (1970) proposed the term debris flood for unstructured conglomerates which contain less than 1 percent silt and clay. He described conglomerates from Devonian alluvial fans as being poorly sorted, coarse and lacking a well developed clast framework with random orientation of clasts and an association with sandstone of fluvial aspect. Miall's deposit and one described by Fisher (1971) from the Vasquez Formation of California closely resemble the unsorted, matrix-supported conglomerate lithofacies (Gms).

Non-erosive basal contacts, a sand-sized, matrix-supported framework, random orientation of clasts, and association with fluvial deposits suggest a debris flow or viscous debris flood origin for this lithofacies. Deposition from a viscous flow is suggested by the matrix-supported framework and lack of erosive basal contacts. Because a continuum exists between viscous debris flood deposits and debris flow deposits (movement in laminar flow), the Gms lithofacies could be interpreted as a viscous debris flood deposit. In regards to the general usage of the terms, I am identifying the Gms lithofacies as a debris flow deposit.

In summary, the conglomeratic lithofacies are the dominant lithologies in the basal "lower clastic unit". All three lithofacies are associated in the Bozeman area exposures. The Gms lithofacies represents only a minor proportion of the conglomeratic deposits in the "lower clastic unit". Gm_1 lithofacies occurs without the associated conglomeratic lithofacies in the Dillon area exposures.

Trough Cross-bedded Sandstone Lithofacies St

Description

A predominant structure in coarse- to fine-grained sandstones of the "lower clastic unit" are large-scale, trough cross-beds. In the Bozeman area, lenses (up to 4.0 feet; 1.2 m thick) of trough cross-bedded sandstones are associated with the conglomeratic lithofacies (Gm_1 and Gm_2). Sharp to scoured contacts separate these lithofacies (Fig. 4). In the Dillon area exposures, the trough cross-bedded sandstone lithofacies is more dominant than in the Bozeman area, and

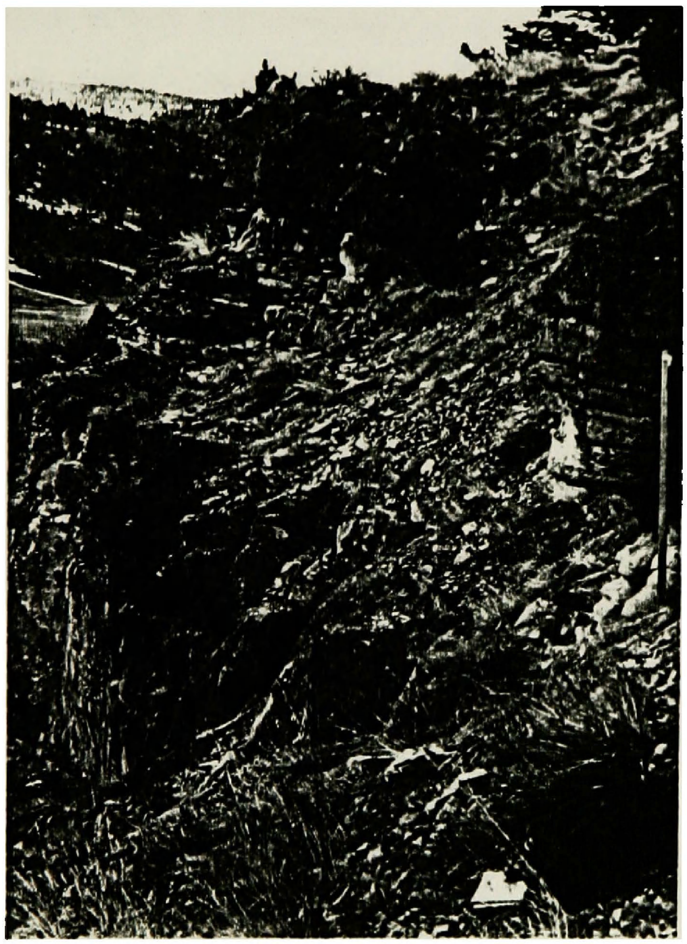


Figure 4. Interlensed lithofacies Gm_2 and St in sharp contact forming resistant ledge characteristic of the basal "lower clastic unit". Jacobs staff is 5 feet.

is associated with the siltstone and mudstone lithofacies (Fm). Sharp contacts separate these two lithofacies. The trough cross-bedded sandstone lithofacies forms tabular-shaped beds 4.0 to 39.0 feet (1.2 to 12 m) thick which are traceable over the distance of outcrop for hundreds of feet. This type of laterally continuous deposit does not occur in the Bozeman area exposures.

Interpretation

Trough cross-stratification is formed by the migration of sinuous, dune-shaped bedforms (Allen, 1977; Harms and Fahnestock, 1965; Miall, 1977; Reineck and Singh, 1980 and Collinson, 1978). Allen (1977) suggests that trough cross-stratification originates when a sinuous crested bedform migrates downstream, infilling an erosional scour or scoop-shaped depression with curved cross-strata. Preservation of these bedforms requires the infilling depression be cut below the general level of erosion. Recent studies of braided outwash streams in Alaska and of ancient fluvial systems in general demonstrate the presence of dune forms and their associated trough cross-stratification as active channel fill deposits (McGown and Groat, 1971; Steel, 1974; Smith, 1970; Eynon and Walker, 1974 and Harms and Fahnestock, 1965). The trough cross-beds observed in the "lower clastic unit" are similarly interpreted as the deposits of a migrating dune-shaped bedform within a channel. Continual flow within the range of dune formation would lead to a train of migrating dunes which would deposits cosets of trough cross-bedded sandstones. The difference in deposit shape (lenses in the Bozeman area and laterally-extensive, tabular beds in the Dillon area) reflect the different fluvial system which deposited the trough cross-bedded sandstone (St) lithofacies (see Environmental Interpretation section).

Planar Cross-bedded Sandstone Lithofacies Sp

Description

Minor occurrences of planar cross-bedded sandstone are found in the "lower clastic unit". Single sets of tabular, low-angle planar cross-beds are associated with the conglomeratic lithofacies (Gm_1, Gm_2 and Gms) in the Bozeman area exposures and with the trough cross-bedded sandstone lithofacies (St) in the Dillon area exposures (Fig. 5). Single sets range in thickness from less than 1.0 to 4.0 feet (0.3 to 1.2 m) and are traceable laterally the length of outcrop in the Dillon area. In the Bozeman area, planar cross-beds are less persistent laterally and exhibit erosional contacts with the associated conglomeratic (Gm_1, Gm_2 and Gms) lithofacies. Individual sets of planar bedded sandstones predominate over the occurrence of planar cross-bedded sets. The sandstone in all cases is fine to medium grained.

Interpretation

Planar cross-stratification is formed by the migration of low-sinuosity to straight crested sandwaves or transverse bars along which gravitational movement of sediment down the slip face result in planar cross-stratification (Allen, 1977; Harms, 1975 and Harms and Fahnestock, 1965). As velocity increases and suspension and gravity-gliding of grains build out the foreset, a decrease in amplitude and

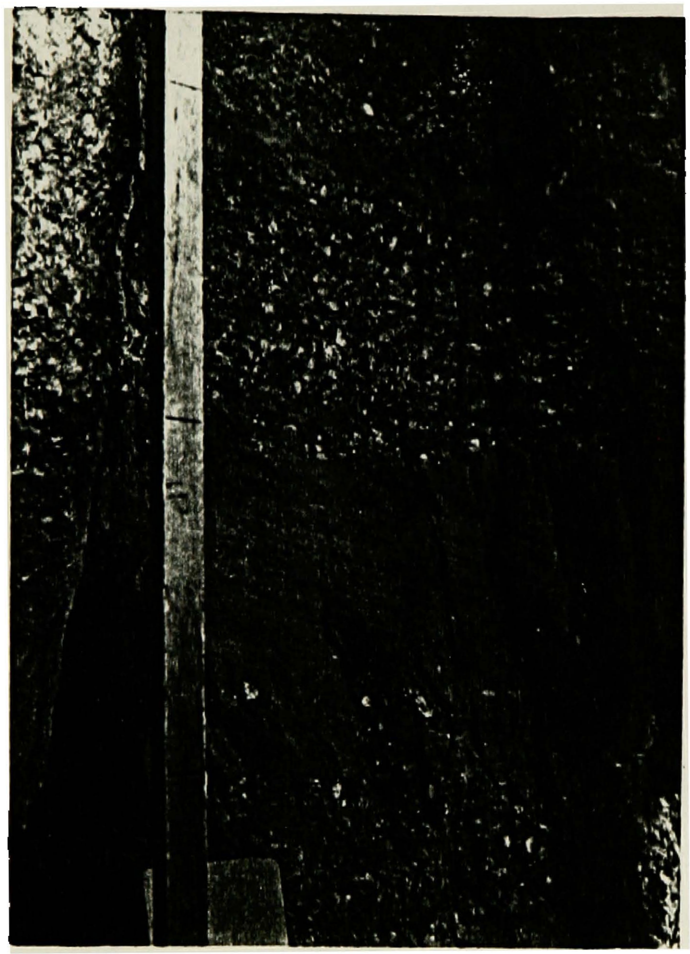


Figure 5. Thin deposit (center of photo) of low angle, planar cross-bedded sandstone (lithofacies Sp) interlensed with conglomeratic lithofacies Gm_1 (above) and Gm_2 (below) and trough cross-bedded sandstone lithofacies St in the Bozeman area. Jacobs staff in feet.

a more tangentially based cross-bed result (Harms, 1975). Tabular, planar cross-stratified sets commonly form thick, isolated deposits with long lateral dimensions relative to set thickness. Sand waves which deposit planar cross-beds are produced under lower flow velocities than dune bedforms which deposit trough cross-beds (Harms, 1975). In a fluvial setting, planar cross-bedded sandstones commonly overly bed-forms deposited by higher-velocity flow (McGowen and Groat, 1971 and Harms, 1975). Some authors studying recent fluvial systems have found an increase in planar cross-strata in the distal reaches; this increase is consistent with their forming under low energy flow conditions (Smith, 1974; McGowen and Groat, 1971; Eynon and Walker, 1974, and Hein and Walker, 1977).

Low angle, planar cross-bedded sandstones in the "lower clastic unit" represent deposits formed by the migration of sandwaves or transverse bar forms. The association of this lithofacies (Sp) with the conglomeratic (Gm_1, Gm_2) and trough cross-bedded sandstone lithofacies (St) suggests a transverse bar or sandwave mode of origin. Thick, single sets of planar cross-bedded sandstone (Sp) may have formed as a sand drap on the side of a longitudinal bar. The association of thick, individual planar sets with the Gm_1 lithofacies in the Bozeman area supports this origin. Planar cross-bedded sandstones associated with trough cross-bedded sandstones in the Dillon area formed in transverse bar or sandwave bedforms within a channel.

Horizontally Stratified Sandstone Lithofacies Sh

Description

Associated with the conglomeratic (Gm_1, Gm_2), trough cross-bedded (St) and planar cross-bedded (Sp) lithofacies in the Bozeman area, are deposits of horizontally to sub-horizontally stratified, coarse- to fine-grained sandstone. The stratification consists of an alternating coarse-grained, black chert-rich lamina and a fine-grained, white chert- and quartz-rich lamina. A couplet consisting of a coarse- and fine-grained lamina is approximately 1.0 to 2.0 centimeters thick while the thickness of individual lamina varies. This lithofacies overlies conglomeratic and cross-stratified sandstone sequences. Lens-shaped deposits of this lithofacies range from 0.5 to 4.0 feet (0.1 to 1.2 m) thick.

Interpretation

Recent flume studies led people to believe that laminated, size-graded sands originated during upper flow regime plane bed transport (Harms and Fahnestock, 1965; McBride et al., 1975, and Smith, 1971). However, more recent observations in flume and fluvial environments demonstrate that alternating coarse- to fine-grained, horizontal laminations form by migration of low-amplitude ripples or small scale sandwaves during low flow regime conditions in shallow water (McBride et al., 1975, and Smith, 1971). Migration of low-amplitude ripples or small sandwaves produce size-graded, horizontally-laminated sands when coarse material in the lee of the form migrating downstream covers the finer material on the stoss side of the next bedform (McBride et al., 1975). Sands continue to aggrade in this fashion if the water level rises gradually. If the water level rapidly increases, ripple cross-laminated or deeper-water trough cross-bedding may result. Average depths used in flume studies to form these laminations and depths observed on the Platte River by Smith (1971) were all less than five centimeters (McBride et al., 1975).

Horizontally to sub-horizontally stratified, size-graded sandstones in the "lower clastic unit" are interpreted as deposits resulting from the migration of small sandwaves or low-amplitude ripples in shallow water. Flume studies of McBride and others (1975) showed that deposits of alternating, size-graded sands form during shallow (5.0 cm), lower flow regime conditions and not during upper flow regime plane bed conditions. This interpretation of shallow, low flow strength conditions is consistent with the observed occurrence of the horizontally stratified sandstone lithofacies (Sh) overlying conglomeratic (Gm_1 and Gm_2) and cross-stratified sandstone lithofacies (St and Sp). The thick deposits of this lithofacies (up to 4.0 feet, 1.2 m), suggest that aggradation kept pace with gradually increasing depth of flow.

Ripple-Laminated Sandstone Lithofacies Sr and Sre

Description

Ripple-laminated sandstones occur as part of two different lithofacies associations within the "lower clastic unit". The first is of fine- to medium-grained, ripple-laminated sandstone in fining-upward sequences associated with the conglomeratic (Gm_1 and Gm_2) and cross-bedded sandstone (St and Sp) lithofacies (Fig. 2). The ripple-cross-laminated sandstone shows size-graded, discontinuous laminations of medium-grained, black chert rich sandstone with discontinuous, fine-grained quartz and white chert rich sandstone. Beds of complex, trough-shaped ripple cross-stratification (2 to 4 cm wide and 1 to 2 cm thick) range in thickness from 0.6 to 2.0 feet (0.2 to 0.6 m). Gradational to sharp contacts are often seen with the underlying coarser-grained lithologies within a fining-up sequence.

The second association of ripple-laminated sandstones is with the muddy sandstone to calcareous sandy mudstone (P) and mudstone/silt-stone (Fm) lithofacies. Laterally impersistent, but tabular-shaped thin sandstone beds occur at several localities (section 1, 2, 4, 7, and 8) near the muddy sandstone to calcareous sandy mudstone litho-facies (P). Very fine- to fine-grained, ripple cross-laminated (1 cm. thick and approximately 2 cm. wide) sandstones form beds that vary in thickness from 2.0 (0.6 m) to 5.0 (1.5 m) feet. The ripple cross-laminated sandstone lithofacies has sharp contacts with the associated lithofacies (Fm and P). Thin sections of this lithology show a clean, well-sorted, very fine-grained sandstone.

Interpretation

During waning flow, finer-grained materials are moved in bedforms similar to dunes but of much smaller scale (Allen, 1963 and Harms, 1975). Small scale, trough cross-laminated sandstones are formed by the migration of dune-shaped ripples, namely linguoid and lunate forms (Allen, 1977; Harms and Fahnestock, 1965; Miall, 1977 and Reineck and Singh, 1980). Aggradation of migrating ripples give rise to small scale (less than 4.0 cm. in height) cross-lamination. Current ripples of low-amplitude deposited the cross-laminated sandstone (Sr) associated with the coarser conglomeratic and sandstone lithofacies in the "lower clastic unit". The stratification of medium-grained, black chert rich lamina and fine-grained, quartz and white chert rich lamina support deposition by a low-amplitude ripple form of sufficient size to form cross-laminations.

The finer-grained, well-sorted,ripple-laminated sandstones associated with the mudstone/siltstone (Fm) and muddy sandstone to calcareous sandy mudstone (P) lithofacies may represent either aeolian reworked overbank sands or waning flood deposited overbank sands. Several studies of aeolian sands report well-sorted, fine grain sized textures (Glennie, 1970; Reineck and Singh, 1980; Allen, 1977, and Walker, 1980). Allen, (1977) proposes the following characteristics as suggestive of a wind-blown origin for sand: a lack of clay or silt matrix; a fine grain size; well to very well sorted sand, and a close spatial association with deposits of fluvial or littoral origin. He does not mention aeolian sandstone forming a deposit comprised of ripple-laminated bedforms. These textures by themselves are not indicative of an aeolian deposit, but the stratigraphy of the deposit in which impersistent, yet tabular sandstone, maroon mudstone/siltstone (lithofacies Fm) and muddy sandstone to calcareous sandy mudstone (lithofacies P) occur without channel type sandstones (lithofacies St and Sp) suggest a floodplain environment on which either aeolian processes reworked fine flood deposits or a major flood deposited fine-grained sandstone during the waning stages far from any recognized channel.

Mudstone/Siltstone Lithofacies Fm

Description

The upper part of the "lower clastic unit" consists predominantly of mudstones and siltstones. These overlie the conglomeratic (Gm_1, Gm_2 and Gms) and cross-bedded sandstone (St, Sp, Sh) lithofacies throughout the study area. Sedimentary structures are poorly exposed in this lithofacies, however minor burrows, mudcracks, ripple laminations and thin horizontal laminations are present locally. More commonly, platy fractured siltstone and mudstone fragments form a slope in which primary sedimentary structures are not preserved. Minor, thin interbeds of gray to green mudstones, less than 1.0 inch (2.5 cm) thick, have gradational contacts with surrounding maroon siltstones and mudstones. In the Bozeman area exposures, these mudstones and siltstones are associated with the muddy sandstone to calcareous sandy mudstone lithofacies (P) and with calcareous, nodular horizons which increase in abundance higher in the section ("lower calcareous unit"). In the Dillon area exposures, this mudstone/siltstone lithofacies is associated with trough cross-bedded and planar cross-bedded sandstone lithofacies (St and Sp) which crop out as tabular-shaped beds encased in the mudstone/siltstone lithofacies. Commonly these mudstones and siltstones are mottled a tan-brown.

Interpretation

The association of red beds with minor gray and green beds, mud-cracks and burrows in vertical succession overlying conglomerates and sandstones is well documented in the literature (Allen, 1977; Collinson, 1978 and Van Houton, 1973). This sequence is interpreted as accretionary deposits related to overbank flooding and settling of fines within the floodplain. The red coloration of the majority of siltstones and mudstones has been attributed to the level of the water table after deposition (Collinson, 1978). An oxygenated environment in which iron-bearing minerals chemically weather will produce a red colored sediment (Van Houton, 1973). The mudstone/siltstone lithofacies (Fm) contains features commonly attributed to overbank sedimentation. The occurrence of minor gray and green shales, mud-cracks, minor burrows and the vertical succession of this lithofacies overlying the conglomeratic and sandstone lithofacies is interpreted as overbank deposits associated with a higher sinuosity fluvial system. Although the association of lithologies observed in the mudstone/siltstone lithofacies have been documented from environments with semi-arid, alkaline climates (Allen, 1974), this does not unquestionably point towards that same type of climate during "lower clastic unit" deposition. The interpretation of overbank and alluvial plain origin describes the associated features well, especially in the western exposures where the mudstone/siltstone lithofacies is associated with tabular deposits of trough and planar cross-bedded sandstones.

Muddy Sandstone to Calcareous Sandy Mudstone Lithofacies P

Description

An unusual lithology composed of varying percentages of clastic and carbonate components occurs near the top of the "lower clastic unit". In hand specimen, a striking characteristic is a "floating-grain texture". This lithofacies is more resistant and indurated than the surrounding siltstones. The outcrop surface is mottled and bulbous.

This lithofacies varies from a muddy sandstone to a calcareous sandy mudstone and is associated with the mudstone/siltstone and ripple-laminated sandstone lithofacies (Fm and Sre). Lateral extent of this discontinuous lithofacies varies and contacts with surrounding lithologies are gradational. This lithofacies is restricted to the Bozeman area exposures. In hand specimen, these rocks show a mottled orange-tan brown coloring in which medium- to fine-grained red, black, tan, and white chert and quartz clasts float in a highly indurated siliceous and calcareous matrix. Reaction in HCL varies from slow in some samples to effervescent in others. In thin-section, these rocks range from calcareous, medium-grained sandstones to sandy intramicrites. Intraclasts of nonresolvable micrite mud surrounded by microspar rims are enclosed in a micritic matrix. Microspar appears to be replacing an amorphous siliceous matrix in all the slides. Fractures are filled with blocky sparry calcite and rimmed with iron-oxides (hematite).

The floating grain texture is a result of replacement of siliceous matrix by microspar and micrite and possibly displacement of the medium-grained detrital clasts as the microspar crystallized. Detrital grains show no replacement by calcite and commonly are coated around their edges by micrite (a cutan) or a rim of microspar (Fig. 6). In addition to floating grain texture and coatings (cutans), matrix and grains are brecciated and fractured. Large 'blocks' (2mm wide) of densely micritized rock material are juxtaposed next to 'blocks' of sandstone with a siliceous matrix in which calcite replacement is beginning. Irregular fractures filled with microspar and sparry calcite delineate small 'blocks' of rock material (Fig. 7). These irregular fractures have been attributed to expansion of rock material during evaporative crystallization of calcite in the vadose environment (Watts, 1980 and Brewer, 1964).

Interpretation

Vadose zone cementation processes occur when an area is emergent for a time period in which detrital input is limited (Allen, 1974). Under conditions favorable to calcium carbonate precipitation, the longer the period of emergence, the greater the development of calcareous horizons. Calcareous horizons or caliches form when a source of calcium carbonate and a mechanism for precipitation exist (Gardner, 1972). Alternating of wet and dry periods during which water percolates through a sediment and is then evaporated, leaving behind a concentration of carbonate salts, has been proposed as the mechanism

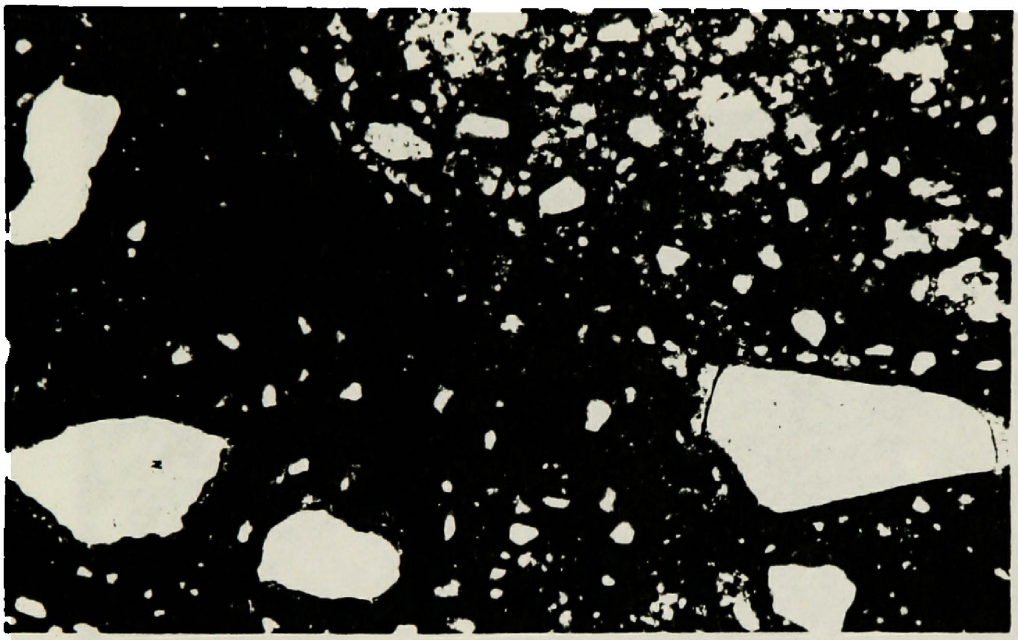


Figure 6. Textures indicative of vadose zone cementation are shown in this photomicrograph of the muddy sandstone to calcareous sandy mudstone lithofacies (P). These textures include a 'floating grain texture' in which clastic grains are separated from each other by a micritic matrix, cutans or micritic rinds which coat clastic grains (lower left corner) and glabules or patches of densely micritized rock material (darkest areas in photomicrograph). Magnitification 12.5X.

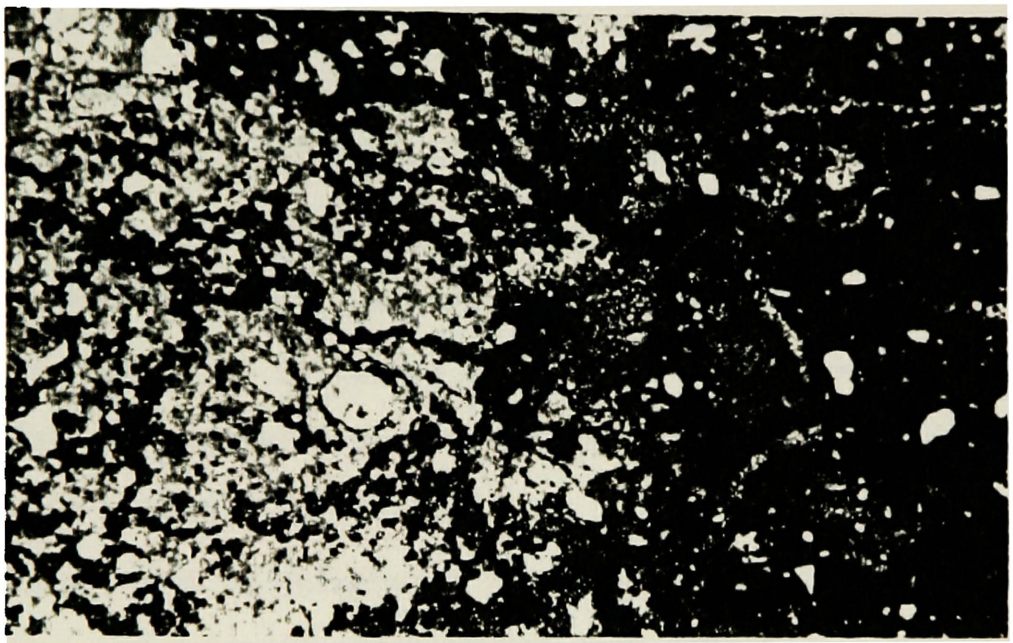


Figure 7. Hematite and microspar replace siliceous matrix along fractures (left). Right side of photo contains densely micritized rock material fractured into blocks, fractures are filled with microspar. Magnification 10X.

responsible for development of calcareous horizons (Collinson, 1978). Soil or vadose zone textures have been described by Knox (1977), Reeves, (1976), Watts (1978), Brown (1956), James (1972), Brewer (1964), Smoot (1977), and Goodie (1973). Replacement and/or displacement of detrital grains by growth of calcite has been described from fluvial (Watts, 1980), aeolian/alluvial (Gardner, 1972), and aeolian/littoral (Knox, 1977) environments. This growth of calcite creates a characteristic floating grain texture (Watts, 1980 and Knox, 1977). Micro-textures such as brecciation of cryptocrystalline calcite matrix, coatings or cutans around detrital grains, and concentrated blebs or glaebules of micrite also characterize vadose zone deposits (Brewer, 1964, Chs. 10-14).

The muddy sandstone to calcareous sandy mudstone lithofacies is interpreted as a deposit in which vadose zone cementation processes occurred and soil type textures developed, however, a soil horizon or caliche profile did not develop. The characteristic floating grain texture, formed by displacive and/or replacive growth of calcite, the highly indurated fabric as opposed to the slope forming siltstones which surround it and soil micro-textures support a vadose zone environment of formation for this lithofacies. In section 1, a series of samples show an increasing calcification up section from 51.0 to 80.0 feet. In recent caliche horizons, the uppermost levels are more calcified than the stratigraphically lower sections (Knox, 1977). Since clear soil horizons do not occur, I refrain from the use of the term caliche and interpret the muddy sandstone to calcareous sandy mudstone lithofacies (P) as an early vadose-zone cemented horizon, possibly formed in an ephemeral lake in which the conditions for carbonate concentration and precipitation and soil texture development existed.

PROVENANCE OF THE "LOWER CLASTIC UNIT"

The conglomeratic sandstone and sandstone lithologies of the "lower clastic unit" were looked at in thin section in order to verify the proposed provenance of Paleozoic and Early Mesozoic miogeoclinal strata. Of forty-six thin sections; 80% were chert-arenites; 17.5%, sublith-arenites; and 2.5%, quartz arenites. Cherts of various colors both fossiliferous and non-fossiliferous comprise the majority of clasts. Common (clear, with near straight extinction) and vacuole-containing varieties are the dominant mono-crystalline quartz types. Some quartz with needles of moderate birefringence (rutile?) were present and extremely minor occurrences of stretched metamorphic quartz and detrital biotite were found in the most western outcrop sampled (section 14). The distribution of chert types varies slightly from west to east. In the western area exposures, a minor but distinctive green porcellanite occurs and black and red chert comprise a larger percentage of the total chert present than in the eastern exposures. Fossil remains within chert clasts are so thoroughly silicified that specific identification was not possible; however spicules, bryozoans and pisolitic remnants are present. Phosphatic material occurs in some of the brown cherts. Cherts observed in this study are similar to varieties described from equivalent strata south of here in the Idaho-Wyoming thrust belt (Furer, 1970). Quartz overgrowths (Fig. 8) and calcite are the major cementing agents. Calcite is dominant in the western exposures and quartz overgrowths,

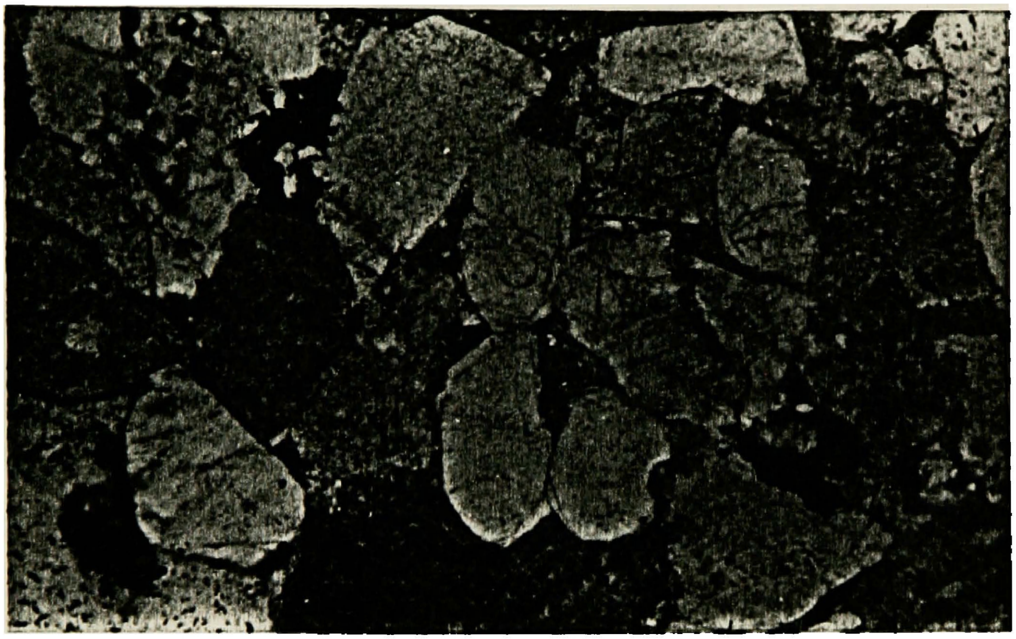


Figure 8. Quartz overgrowths seen on quartz grains in center of photograph are a major cementing agent in the basal "lower clastic unit". Hematite (dark patches) also forms pore-filling cement. Plane light. Magnification 16X.

calcite and ferrugenous cements all occur in comparable amounts in the eastern areas. Pore-filling chlorite was found in 4% of the slides, all from section 14, the westernmost sampled.

The provenance of the "lower clastic unit" has been proposed as Paleozoic and Early Mesozoic miogeoclinal sediments from highlands west of Montana (Suttner, 1969; Roberts, 1972 and Furer, 1970). Clasts described by Furer (1970), which appear similar to some described from the "lower clastic unit" occurred with limestone clasts dated as middle to late Pennsylvanian. Phosphatic chert is abundant today in exposures of the Permian Phosphoria Formation. These sparse data suggest a Pennsylvanian to Permian aged source for the Early Cretaceous rocks south of this area and most likely for the "lower clastic unit" as well. Although this clast has not been described from "lower clastic unit" equivalents, the green, porcellanitic clasts may be derived from devitrified volcanic ash beds located in Idaho and Wyoming, possibly of Jurassic age (Peterson, 1981, Pers. Comm.).

Siltstones and shales overlying the basal "lower clastic unit" reflect a clay mineralogy different from previously described clay mineralogies in southwestern Montana and northern Wyoming. Montmorillonite has been described from "lower clastic unit" equivalents in the Big Horn Basin (Moberly, 1960). The presence of montmorillonite suggests a volcanic source. In a study of the entire Kootenai Formation throughout southwestern Montana, Suttner (1968) found illite the most abundant clay mineral present. He interpreted the illite (1 Md variety) as detrital from Paleozoic sedimentary source rocks.

Ten oriented and glycolated clay samples from sections 14, 7 and 1 in southwestern Montana indicate that kaolinite is the most abundant clay mineral present. No montmorillonite peaks were observed from these samples. Sequentially subordinant amounts of illite, quartz, halite, heterogeneous mixed-layer smectite-illite and chlorite are also present. The presence of kaolinite was confirmed in samples containing both kaolinite and chlorite by heating the samples to 500 degrees celsius for one hour. It was not determined whether the kaolinite was detrital or diagenetic, hence climatic indications cannot be made.

ENVIRONMENTAL INTERPRETATION

The "lower clastic unit" of the Kootenai Formation was deposited by two different fluvial systems on an alluvial plain complex near the Early Cretaceous foreland basin's western margin. Initial deposits reflect deposition from a high energy, braided fluvial system which was replaced by a lower energy, higher sinuosity fluvial system. The association and distribution of lithofacies vary from Dillon to Bozeman.

Braided Stream Facies

Basal "lower clastic unit" lithofacies reflect deposition by a braided stream system. The braided stream facies in the Dillon (western) area exposures is represented by the massive, grain-supported conglomerate lithofacies (Gm_1). There is a distinct lack of other fluviatile features in this lithofacies in western exposures. The massive, grain-supported lithofacies is coarser grained and lacks cross-stratification compared to this lithofacies in the Bozeman area. The thin, coarse, massive and widespread occurrence (Roberts, 1972; Eyer, 1969; Furer, 1970 and Suttner, 1969) of this conglomerate lithofacies reflects high energy, transport dominated processes which reworked the coarse sediment into a massive gravel lag.

To the east, the basal "lower clastic unit" is characterized by more typical braided fluvial features (Fig. 9). Here the massive, grain-supported conglomerate lithofacies (Gm_1) is vaguely horizontally

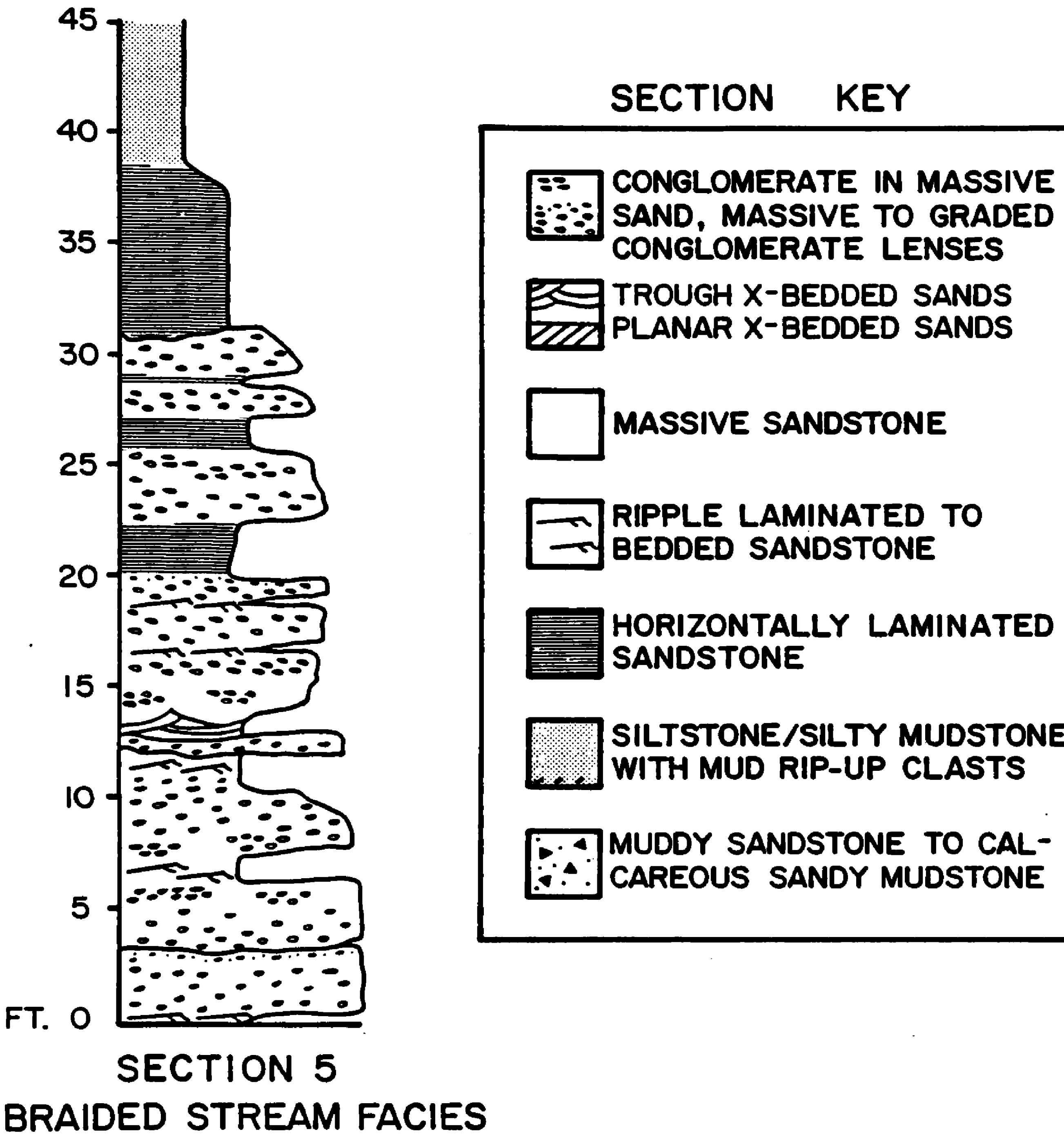


Figure 9. Representative section of the braided stream facies in the Bozeman area. Variously-sized, interlensed conglomeratic and sandstone lithofacies characterize this facies in eastern area exposures. (This key applies to following sections in text as well).

stratified and finer grained. This lithofacies is interpreted as longitudinal bar deposits which are interlensed with channel fill deposits, lithofacies Gm_2; thin debris flow deposits, lithofacies Gms; and channel sandstones, lithofacies St, Sp, Sh and Sr. The rapid lateral and vertical lithofacies variation and the variously sized, lens-shaped deposits reflect variable flow energy and rapidly changing conditions of bed formation and destruction common to braided systems. Within the braided stream facies there is a distinct lack of bedforms with developed slip faces. Smith (1970) concluded that in proximal to medial braided (high energy) environments, coarse material is transported in sheets depositing bar forms which lack a slip face and therefore planar cross-stratification. Distal (lower energy) braided environments, carrying finer grained material develop bars with a slip face, thus the proportion of planar cross-bedding increases in distal braided environments. The lack of planar cross-bedded gravels and association of minor, thin debris flow deposits (lithofacies Gms) support the interpretation of a high energy environment of moderate relief in which braided streams carried material east from major source areas in foreland fold and thrust terranes to the west. Since the speculated source terranes for the "lower clastic unit" lie far west of this area, the presence of debris flow deposits suggest a topography of moderate relief within the foreland basin.

High Sinuosity Stream Facies

In sharp contact, overlying the deposits of the braided stream facies are associations of finer-grained lithologies interpreted as deposits of a higher sinuosity stream system. In the Dillon area, a fining up sequence of trough cross-bedded (St) and low-angle, planar cross-bedded (Sp) sandstone lithofacies outcrop in tabular shaped beds. These laterally persistent beds are surrounded by the maroon mudstone/siltstone lithofacies (Fm). This fining up sequence within tabular shaped sandstone bodies repeats itself throughout the upper "lower clastic unit" in the Dillon area. These tabular shaped sandstone bodies in which cross-bedded lithofacies (St and Sp) predominate, may represent a sandy anastomosing stream complex in which migration of the active channel complex deposited tabular shaped sandstone bodies. These blanketed the western portion of the study area during periods of high sediment influx. Tabular shaped sandstone beds are not found in the Bozeman area exposures (Fig. 10).

In the Bozeman area, continuous fine-grained deposits which include a distinct muddy sandstone to calcareous sandy mudstone (lithofacies P) predominate (Fig. 11). Formation of vadose zone cementation and microstructures in this lithofacies require subaerial exposure and episodic influxes of water followed by evaporative periods. These conditions and the association with the mudstone/siltstone lithofacies (Fm) and the ripple-laminated sandstone lithofacies (Sre) without association of the cross-bedded sandstone lithofacies (St and Sp) suggest an ephemeral lake origin for lithofacies P. Development of ephemeral lakes may have originated during wet periods in which the

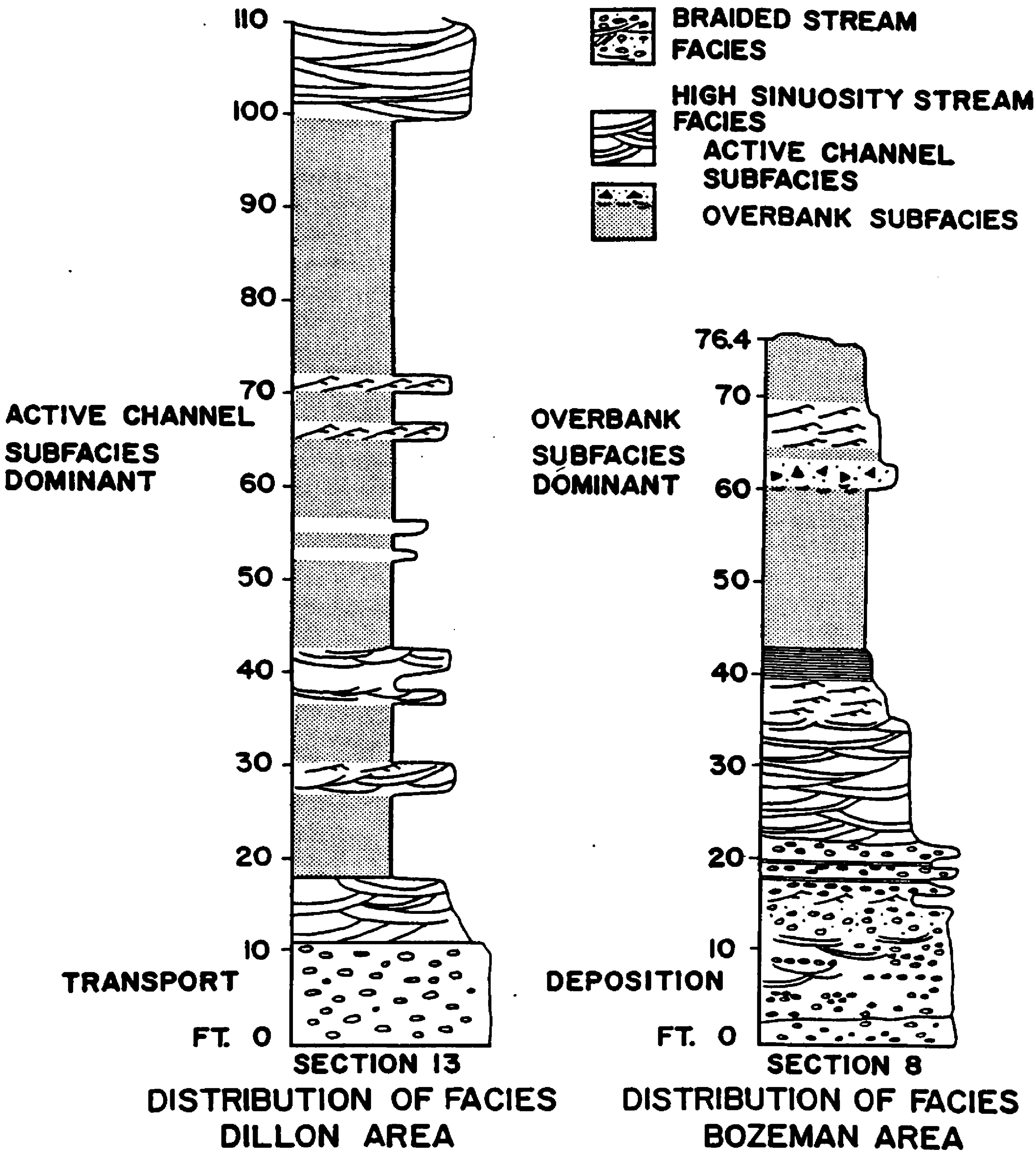


Figure 10. Distribution of facies throughout the study area.

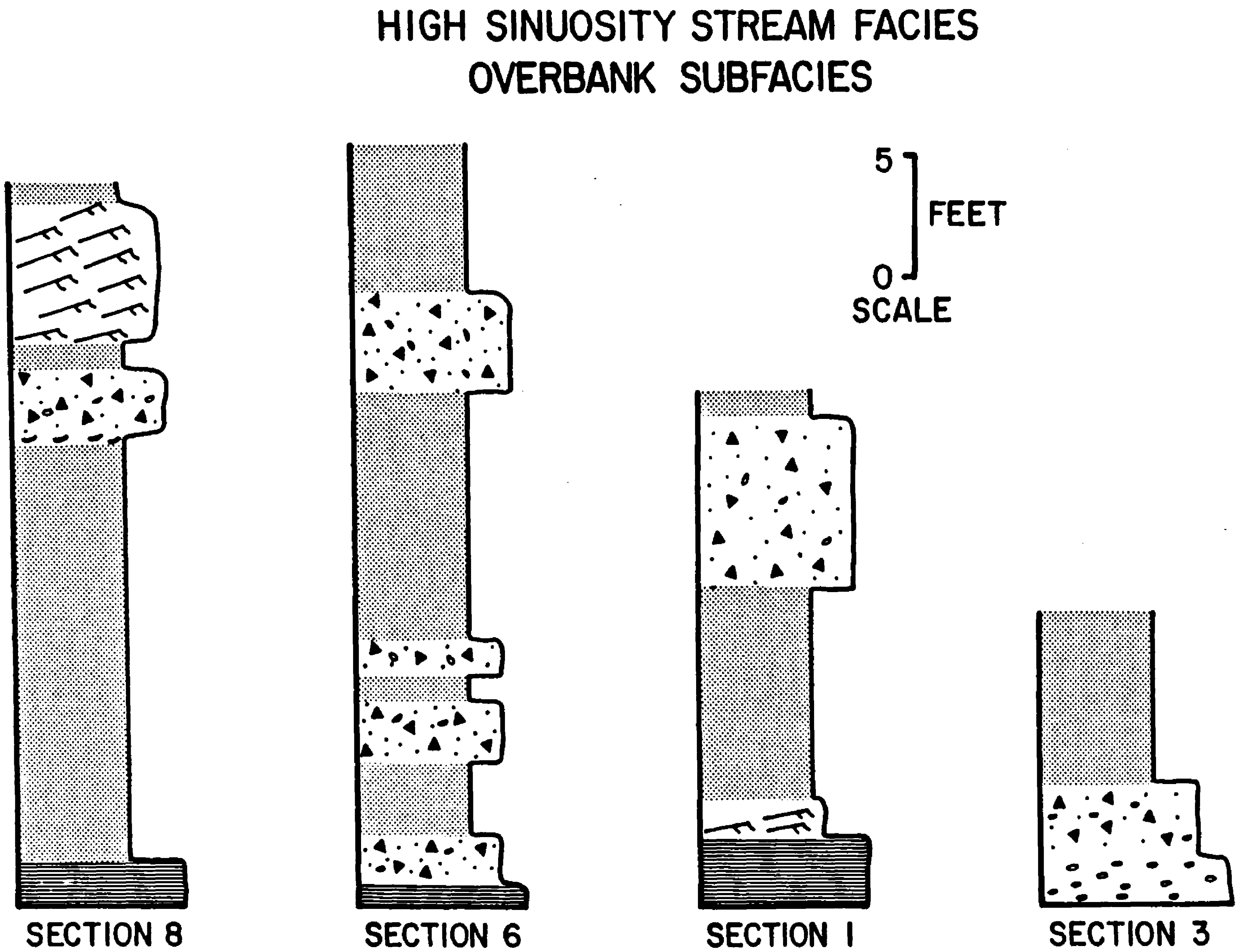


Figure 11. Various associations of the muddy sandstone to calcareous sandy mudstone lithofacies (P) with lithofacies Fm and Sre in the Bozeman (eastern) area exposures.

alluvial plain was covered with water. As flood waters receded, areas of ponding developed, and this lithofacies formed.

The lateral distribution of lithofacies in the braided stream facies reflects transport dominated processes which reworked coarse clastics into a massive gravel lag to the west and deposition dominated processes both fluvial and debris flow in origin which deposited interlensed conglomeratic and sandstone lithofacies to the east. Within the high sinuosity stream facies, the active channel subfacies predominates in the western areas and the overbank subfacies predominates in the eastern areas (Fig. 10). This configuration for "lower clastic unit" depositional environments is in general agreement with regionally described settings (Eyer, 1969; Peterson, 1966 and Eisbacher, et al., 1974). Eyer (1969) and Eisbacher and others (1974) suggest a large north-south trending trough existed adjacent to the early foreland highlands during Early Cretaceous time. The "lower clastic unit" which is biostratigraphically bracketed as Early Cretaceous, reflects deposition on an alluvial plain in the foreland basin in which depositional processes changed from braided to higher sinuosity (possibly a sandy anastomosing system) (Fig. 12).

A number of events may be responsible for the observed change from braided to higher sinuosity deposits. Some probable controls on "lower clastic unit" deposition include a change in regional climate related to the establishment of an Andean-type margin to the west, such as occurred in Late Jurassic time; a change in base level as the mid-Cretaceous intracratonic seaway transgressed; a decrease in source

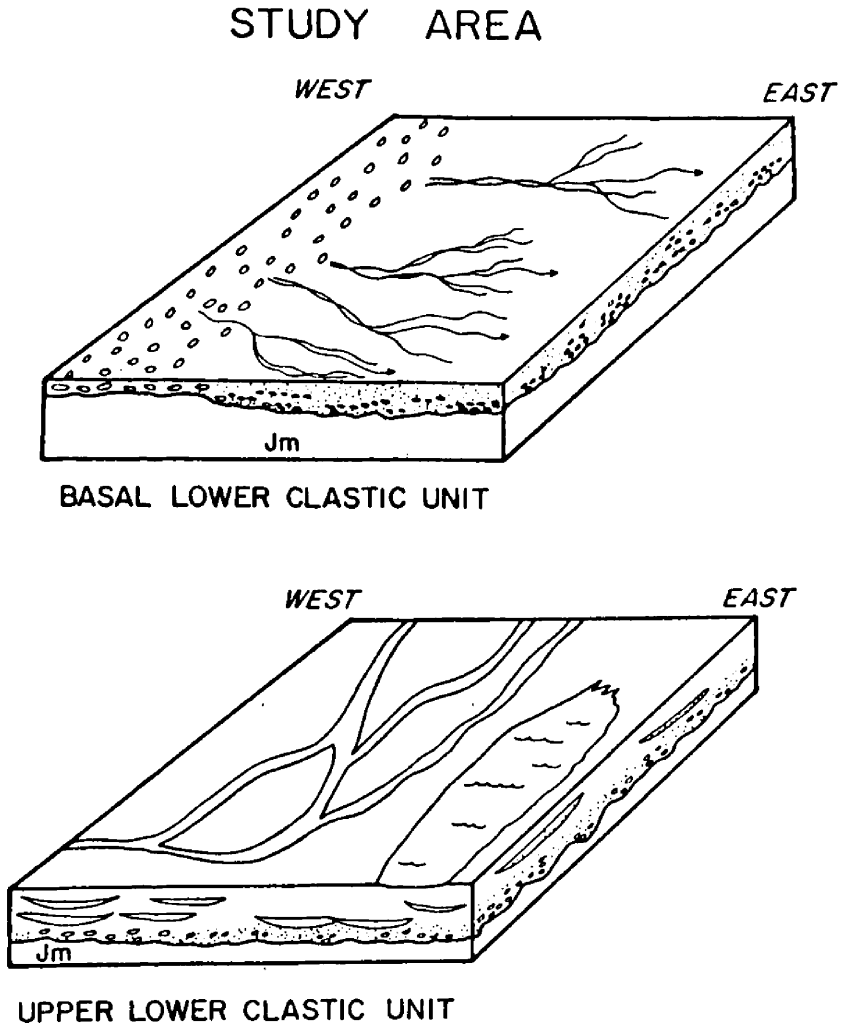


Figure 12. Localized environmental interpretation for the "lower clastic unit" of an alluvial plain with moderate topography situated near the western margin of the Early Cretaceous foreland basin.

terrane such as would occur if only pulses of thrusting provided the initial highlands in Early Cretaceous time, or a combination of these.

SUMMARY

The stratigraphy of the "lower clastic unit" reflects a change in depositional processes from a braided fluvial to a higher sinuosity system. The distribution of lithofacies deposited by these two systems varies from west to east across southwestern Montana (Fig. 10). The basal "lower clastic unit" was deposited by a braided fluvial system. In the western areas, this facies is represented by a thin gravel lag in the massive, grain-supported lithofacies (Gm_1). To the east, the braided stream facies is represented by a variety of conglomeratic and sandstone lithofacies (Gm_1, Gm_2, Gms, St, Sp, Sh and Sr) which are interlensed both laterally and vertically. This sequence represents the reworking of sediment into bars and channels under changing conditions of flow often associated with a braided environment. Overlying the braided stream facies throughout the area are finer grained deposits of the high sinuosity stream facies (a sandy anastomosing system(?)). The active channel subfacies (St and Sp) predominates in the western area, while the overbank subfacies (Fm, P, Sre) predominates in the eastern areas. These fluvial systems deposited sediment on an alluvial plain near the Cordilleran foreland basin's western margin (Fig. 12). The presence of debris flow deposits indicates relief within the alluvial plain may have been moderate.

The petrography indicates a reworked sedimentary source such as the Paleozoic and Early Mesozoic miogeoclinal strata and an absence of volcanic detritus. Thrusted terranes from the southwest and/or incipient highlands associated with the early emplacement of the Idaho Batholith to the west may have been source areas for the "lower clastic unit". This study indicates Early Cretaceous foreland sedimentation was complex and not simply the result of a single style of fluvial deposition.

Allen, J.R.L., 1963, The classification of cross-stratified units, with notes on their origin: Sedimentology, v. 2, p. 93-114.

_____, 1974, Studies in fluvial sedimentation: implications of pedogenic carbonate units, Lower Old Red Sandstone, Anglo-Welsh Outcrop: Geol. Journ., v. 9, p. 181-204.

_____, 1977, Physical Processes of Sedimentation: London, Allen and Unwin Ltd., 248 p.

Armstrong, F.C., and Oriel, S.S., 1965, Tectonic development of the Idaho-Wyoming thrust belt: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 1847-1866.

Boothroyd, J.C., and Ashley, G.M., 1975, Process, bar morphology and sedimentary structures on braided outwash fans, NE Gulf of Alaska, in Jopling, A.V., and McDonald, B.C., eds., Glaciofluvial and Glaciolacustrine sedimentation: Soc. Econ. Paleontologists Mineralogists Spec. Pub. No. 23, p. 193-222.

Brewer, Roy, 1964, Fabric and mineral analysis of soils: New York, Wiley, 470 p.

Brown, C.N., 1956, The origin of caliche on the northeastern Llano Estacado, Texas: Jour. Geology, v. 64, p. 1-15.

Christopher, J.E., 1975, The depositional setting of the Mannville Group (lower Cretaceous) in southwestern Saskatchewan in Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geol. Assoc. Canada Spec. Paper 13, p. 523-552.

Cobban, W.A., 1955, Cretaceous rocks of northwestern Montana: Billings Geol. Soc. 6th Ann. Fld. Conf. Guidebook, p. 109-119.

Collinson, J.D., 1978, Alluvial Sediments, in Reading, H.G., ed., Sedimentary Environments and Facies: New York, Elsevier, p. 15-59.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage", central British Columbia to central California in Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Soc. Econ. Paleontologists Mineralogists Pacific Coast Paleogeography Symposium 2, p. 1-32.

Eisbacher, G.H., Carrigy, M.A., and Campbell, R.B., 1974, Paleodrainage pattern and late-orogenic basins of the Canadian Cordilleran in Dickinson, W.R., ed., Tectonics and Sedimentation: Soc. Econ. Paleontologists Mineralogist Spec. Paper No. 22, p. 143-166.

Eyer, J.A., 1969, Gannett Group of western Wyoming and southeastern Idaho: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 1368-1390.

Eynon, George and Walker, R.G., 1974, Facies relationships in Pleistocene outwash gravels southern Ontario: a model for bar growth in braided rivers: Sedimentology, v. 21, p. 43-70.

Fisher, R.V., 1971, Features of coarse-grained, high concentration fluids and their deposits: Jour. Sed. Petrology, v. 41, p. 916-927.

Furer, L.C., 1970, Nonmarine Upper Jurassic and Lower Cretaceous rocks of western Wyoming and southeastern Idaho: Amer. Assoc. Petroleum Geologists Bull., v. 54 ~~70~~, p. 2282-2302.

Gardner, L.R., 1972, Origin of the Mormon Mesa Caliche, Clark County, Nevada: Geol. Soc. America Bull., v. 83, p. 143-156.

Glennie, K.W., 1970, Desert Sedimentary Environments: Developments in Sedimentology 14: Amsterdam, Elsevier, 222 p.

Goudie, A.S., 1973, Duricrusts in Tropical and Subtropical Landscapes: Oxford, Clarendon Press, 174 p.

Gustavson, T.C., 1974, Sedimentation on gravel outwash fans, Malaspina Glacier Foreland, Alaska: Jour. Sed. Petrology, v. 44, p. 374-389.

Gwinn, V.E., 1965, Cretaceous rocks of the Clark Fork Valley, central-western Montana: Billings Geol. Soc. 16th Annual Field Conf. Guidebook, p. 34-57.

Hamilton, Warren, 1978, Mesozoic tectonics of the western United States in Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Soc. Econ. Paleontologists Mineralogists Pacific Coast Paleogeography Symposium 2, p. 33-70.

Harms, J.C., 1975, Stratification Produced by Migrating Bedforms, in Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., eds., Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences in Soc. Econ. Paleontologist Mineralogists Short Course No. 2, p. 45-62.

Harms, J.C., and Fahnestock, R.K., 1965, Stratification, bedforms and flow phenomena (with examples from the Rio Grande) in Middleton, G.V., ed., Primary Sedimentary Structures and Their Hydrodynamic Interpretation: Soc. Econ. Paleontologists Mineralogists Spec. Publ. No. 12, p. 84-115.

Hein, F.J., and Walker, R.G., 1977, Bar evolution and development of stratification in the gravelly braided, Kicking Horse River, B.C.: Can. Jour. Earth Sci., v. 14, p. 562-570.

Hooke, R.L.B., 1967, Processes on arid-region alluvial fans: Jour. Geol., v. 75, p. 438-460.

James, N.P., 1972, Holocene and Pleistocene calcareous crust (caliche) profiles: Criteria for subaerial exposure: Jour. Sed. Petrology, v. 42, p. 817-836.

James, W.C., 1977, Origin of non-marine - marine transitional strata at the top of the Kootenai Formation (Lower Cretaceous), southwestern Montana [unpub. Ph.D. thesis]: Bloomington, IN, Indiana University.

Jordan, Theresa, E., 1981, Thrust loads and foreland basin evolution, Cretaceous, Western United States: Am. Assoc. Petroleum Geologists, v. 65, p. 2506-2520.

Kauffman, M.E., 1963, Geology of the Garnet-Bearmouth area, western Montana: MT Bur. Mines and Geol. Mem. 39, 40 p.

Knox, G.J., 1977, Caliche profile formation, Saldana Bay (South Africa): Sedimentology, v. 24, p. 657-674.

MacKenzie, F.T., and Ryan, J.D., 1962, Cloverly-Lakota and Fall River paleocurrents in the Wyoming Rockies: Wyoming Geol. Assoc. 17th Ann. Fld. Conf. Guidebook, p. 44-61.

McBride, E.F., Shepherd, R.G., and Crawley, R.A., 1975, Origin of parallel, near-horizontal laminae by migration of bed forms in a small flume, Jour. Sed. Petrology, v. 45, p. 132-139.

McGookey, D.P., 1972, Cretaceous System, in Geologic Atlas of the Rocky Mountain Region, United States of America: Rocky Mountain Assoc. Geologists, p. 190-228.

McGowen, J.H., and Groat, C.G., 1971, Van Horn Sandstone, West Texas: an alluvial fan model for mineral exploration: Rept. of Inv., Bureau of Econ. Geology, Univ. of Texas, v. 72, 57 p.

McMannis, W.J., 1965, Resume of depositional and structural history of western Montana: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 1801-1823.

McQuire, R.H., 1957, The Lower Cretaceous Kootenai Formation in Granite and Powell Counties, Montana [unpub. M.S. thesis]: Missoula, MT., Montana State University.

Miall, A.D., 1970, Devonian alluvial fans, Prince of Wales Island, Arctic Canada: Jour. Sed. Petrology, v. 40, p. 556-571.

_____, 1977, A review of the braided-river depositional environment: Earth Sci. Rev., v. 13, p. 1-62.

_____, 1978, Lithofacies types and vertical profile models in braided river deposits: A summary in Miall, A.D., ed., Fluvial Sedimentology: Canadian Soc. Petroleum Geologists Mem. 5, p. 597-604.

Moberly, R.M., Jr., 1960, Morrison, Cloverly and Sykes Mountain Formations, northern Bighorn Basin, Wyoming and Montana: Geol. Soc. America Bull., v. 71, p. 1137-1176.

Peck, R.E., 1956, North American Mesozoic Charophyta: U.S. Geological Survey Prof. Paper 294-A, p. 1-44.

Peterson, J.A., 1966, Sedimentary history of the Sweetgrass Arch, in Jurassic and Cretaceous stratigraphic traps, Sweetgrass Arch: Billings Geol. Soc. 17th Ann. Fld. Conf. Guidebook, p. 112-134.

Reeves, C.C., 1976, Caliche: origin, classification, morphology and uses: Texas, Estacado Books, 223 p.

Reineck, H.E., and Singh, I.B., 1980, Depositional Sedimentary Environments: New York, Springer-Verlag, 504 p.

Roberts, A.E., 1972, Cretaceous and Early Tertiary depositional and tectonic history of the Livingston area, southwestern Montana: U.S. Geological Survey Prof. Paper 526-C, 113 p.

Royse, F. Jr., Warner, M.A., and Reese, D.L., 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho-northern Utah, in Bolyard, D.W., ed., Symposium and deep drilling frontiers of the central Rocky Mountains: Denver, Rocky Mtn. Assoc. Geologists, p. 41-54.

Rust, B.R., 1972, Structure and process in a braided river: Sedimentology, v. 18, p. 221-245.

_____, 1978, Depositional models for braided alluvium, in Miall, A.D., ed., Fluvial Sedimentology: Canadian Soc. Petroleum Geologists Mem. 5, p. 604-625.

Sharp, R.P., and Nobles, L.H., 1953, Mudflows at Wrightwood, southern California: Geol. Soc. America Bull., v. 46, p. 547-560.

Smith, N.D., 1970, The braided stream depositional environment: Comparison of the Platte River with some Silurian clastic rocks, northcentral Appalachians: Geol. Soc. America Bull., v. 81, p. 2993-3014.

_____, 1971, Pseudo-planar stratification produced by very low amplitude sand waves: Jour. Sed. Petrology, v. 41, p. 69-73.

Smith, N.D., 1974, Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream: Jour. Geology, v. 82, p. 205-223.

Smoot, J.P., 1977, Origin of the carbonate sediments in the Wilkins Peak Member of the lacustrine Green River Formation (Eocene), Wyoming, USA, in Matter, Albert and Tucker, M.E., eds., Modern and Ancient Lake Sediments: International Assoc. Sedimentologists Spec. Pub. No. 2, p. 107-126.

Steel, R.J., 1974, New Red Sandstone floodplain and piedmont sedimentation in the Hebridean Province, Scotland: Jour. Sed. Petrology, v. 44, p. 336-357.

Stelck, C.R., 1975, Basement control of Cretaceous sand sequences in western Canada, in Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geol. Assoc. Canada Spec. Paper No. 13, p. 427-439.

Stokes, W.L., 1944, Morrison Formation and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. America Bull., v. 55, p. 951-992.

Suttner, L.J., 1968, Clay minerals in the Upper Jurassic-Lower Cretaceous Morrison and Kootenai Formations, southwestern Montana: Wyoming Geol. Assn. Bull., v. 1, p. 5-14.

_____, 1969, Stratigraphic and petrographic analysis of Upper Jurassic-Lower Cretaceous Morrison and Kootenai Formations, southwestern Montana: Amer. Assoc. Petroleum Geologists Bull., v. 53, p. 1391-1410.

Suttner, L.J., Schwartz, R.K., and James, W.C., 1981, Late Mesozoic to Early Cenozoic foreland sedimentation in southwestern Montana: Montana Geol. Soc. Fld. Conf. and Symposium Guidebook to southwestern Montana, p. 93-104.

Van Houten, F.B., 1973, Origin of Red Beds A Review 1961-1972: Ann. Rev. Earth and Planetary Sci., v. 1, p. 39-61.

Walker, T.F., 1974, Stratigraphy and depositional environments of the Morrison and Kootenai Formations in the Great Falls area, Montana [unpub. Ph.D. thesis]: Missoula, MT, Univ. of Montana.

Walker, R.G., 1975, Conglomerate: sedimentary structures and facies models, in Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., eds., Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences: Soc. Econ. Paleontologists Mineralogists Short Course No. 2, p. 133-161.

_____, 1981, Facies Models: Ontario, Canada, Geol. Assoc. Canada, 211 p.

Watts, N.L., 1978, Displacive calcite: evidence from recent and ancient calcretes: Geology, v. 6, p. 699-703.

_____, 1980, Quaternary pedogenic calcretes from the Kalahari (Southern Africa): mineralogy, genesis and diagenesis: Sedimentology, v. 27, p. 661-686.